Desktop Review of Polyacrylamide use in the Australian Cotton Industry

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EXECUTIVE SUMMARY

Polyacrylamide, commonly known as PAM, is a long-chain hydrocarbon of high molecular weight, synthesized from natural gas for a range of industrial and environmental use. In Agriculture, PAM and other polymers have been historically used as a soil conditioner similar to gypsum and lime. The purpose of this review is to establish the extent to which PAM is useful in agricultural application, particularly within the cotton industry in Australia and identify knowledge gaps and make key recommendations for future research, development and extension.

Australian and International agricultural and environmental research reviewed in Section 1 shows that anionic PAM of high molecular weight of food grade quality is possibly the best PAM formulation for land and water application because of its high solubility and purity which is capable of providing substantial benefit at extremely low concentration. High purity of PAM ensures that it contains very little impurities (particularly acrylamide, AMD units from which PAM is synthesized) which could be toxic to aquatic organisms and human. Single dose application of anionic PAM at low concentration (in the range of 1-10 ppm) with irrigation water can cause over 50% reduction in runoff and sediment loss. Other associated benefits with this type of application include reduced transport of nutrients, pesticides, weed seeds, pathogens via runoff and sediment, with little off-site impacts. Due to the need for low application rate, PAM application is economically attractive although repeated applications are necessary to derive full, long term benefit. Despite some indication that PAM degrades over time, information on the breakdown products is limited to AMD only. There is also little knowledge available currently that demonstrates how to remove PAM once it is applied to land.

The usage of PAM is significant in the Australian cotton industry with the potential peak usage of one in five of all Australian cotton fields being treated with PAM for various reasons per season. One of the main reasons for using PAM in cotton fields is to reduce irrigation-induced erosion and increase infiltration in soils with low infiltration. However, the commercial application of PAM has produced inconsistent results affecting further use. The reasons for these inconsistent results are due to a lack of understanding of the scientific and technical requirements for successful PAM application and amelioration. For example, when PAM is applied as a liquid in the irrigation water, its benefits are highly sensitive to dosage rate, water quality and soil type. It is difficult for a cotton grower to control PAM dosage as there is a lack of adequate information on the volume of water that is being delivered to the field. The efficiency of PAM application is further affected as there is not enough information readily available on the quality of irrigation water and soil condition. It may be useful to use other strategies to manage soil erosion and/or address infiltration constraints in cotton fields, but there is no best practice yet identified for cotton to combine traditional methods with application of PAM to produce beneficial, long term results. As growers' capability in monitoring of water application rates improve over time, some improvements in PAM application efficiency are expected. However research, extension and education about the practical application of PAM for cotton growers would be highly desirable.

Using PAM to mitigate seepage and evaporation from dams and channels is an emerging and challenging opportunity that is being currently investigated by growers, PAM suppliers and researchers. However, the scientific basis of using PAM to reduce evaporation and seepage is not known as well as for evaporation control and hence, its practical application remains difficult. A collective effort is needed to better understand this area of opportunity. Supporting research, development and extension in this area would of great strategic advantage for the cotton industry.

1.0 INTRODUCTION

Soil conditioners are a class of chemical substances which either occur naturally or synthesized from other natural products. Since 1950s, soil conditioners were primarily used worldwide as cementing or flocculating agents to improve soil structure through improved aggregate stability and pore distribution. Depending on the application method, soil conditioners react chemically with both mineral and organic components of soil material that gives a distinctive change in the physical behavior of soil. For example, material properties of soil (e.g. soil strength) could be changed by mixing sieved soil with a small quantity of a water soluble soil conditioner known as polyvinyl alcohol or PVA (Misra et al. 1986). Polyacrylamide (abbreviated as PAM) can be considered as a chemical substance similar to other soil conditioners, but with a suitability for a wider range of applications than that has been possible with other soil conditioners in the past.

1.1 WHAT IS PAM?

PAM belongs to a class of synthetic polymers with long-chain chemical structure and high molecular weight. These polymers are commonly derived from natural gas for use in a range of industrial and environmental applications. During synthesis of PAM, the length of the polymer can be varied using ionic substitution that changes its length and molecular weight. These changes in PAM cause a significant change in its chemical behaviour and functional attributes which makes it suitable for a wide range of industrial applications (Sojka et al. 2007). PAM rarely contains hazardous elements (e.g. heavy metals or radionuclide) and due to its low toxicity to the environment and organisms, it is believed to have low environmental and public health impacts, requiring little or no regulations over its widespread use. However, the monomer acrylamide often referred simply as acrylamide (AMD) is a human neurotoxin, which may cause skin and respiratory tract irritation and is classified as a probable human carcinogen (USEPA 1994).

PAM can be synthesized as a neutral, cationic, anionic or amphoteric polymer of vastly different lengths, molecular weights and chemical and physical properties. There are actually hundreds of specific PAM formulations, depending on the polymer's chain length and the kinds of functional groups substituted along the chain. The structure of PAM has some similarity with polyethylene, but the hydrogen on every other carbon is replaced by the amide group $–CONH_2$. A single unit of the polymer is referred to as Acrylamide (USEPA 1994) that can simply be expressed as C_3H_5NO, with a structure similar to that shown in Fig. 1. Acrylamide is a highly water soluble compound with a molecular weight of 71.08.

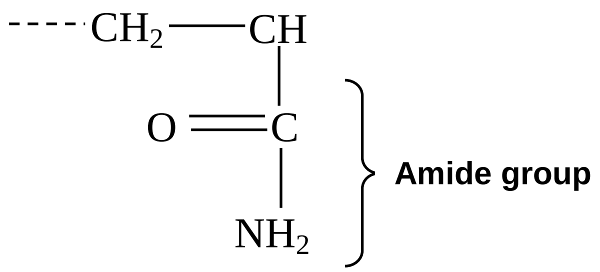

Figure 1. The chemical structure of a unit of Acrylamide. The dashed line indicates possible link to another similar unit that would be repeated to synthesize PAM of longer chain length.

Polyacrylamide molecule is synthesized by repeating the sequence of $–CH_2–CH(CONH_2)–$ units with substitutions of a percentage of the amide ($–CONH_2$) group with another functional group which changes the ionic characteristics and chemical reactivity of the final product. Anionic PAM is the most popular group of PAM compounds which have been found to be most effective in improving land and water management practices.

1.2 ESSENTIAL PROPERTIES OF PAM

The most common PAM formulation used for the treatments of soil, water and food usually contains a sodium ion (Na^+) substituting the amide group of every fifth acrylamide segment that provides a charge site when sodium dissociates in water (Sojka and Surapaneni 2000). Development of charge sites in PAM molecules is important because it allows mutual attraction of PAM molecules to soil colloids, reducing the net charge of colloids which leads ultimately to the formation of clusters of colloids (floccules) which can easily settle out within a soil-water suspension. Other important characteristics of PAM formulations for agricultural use also include a linear rather than cross-linked molecular structure and these formulations do not form gel.

Some PAM formulations may contain more than 150,000 acrylamide units with a molecular weight in excess of 12 Mg $mole^{-1}$ (Sojka and Surapaneni 2000). Early research with anionic PAM of varying molecular weight suggests that PAM with high molecular weight is more effective than low molecular weight in improving infiltration rates and reducing erosion (Levy and Agassi, 1995). As mentioned before, it is difficult to vary molecular weight of PAM without modifying its ionic characteristics (charge density). Polymers are characterized by their molecular weight, molecular confirmation (coiled or stretched), type of charge and charge density, some or all of which affect their interaction with soil (depending on the type and amount of clay present in the soil) in such a way that their effectiveness with flocculation in suspension may be quite different from their effectiveness in increasing soil surface stability against water-drop impact (Ben-Hur 2006). Such variation in the effectiveness of PAM due to the difference in molecular weight and charge density and its dependency on clay content in modifying the infiltration and erosion behaviour of soils has been reported for mine-site rehabilitation (Vacher et al. 2003).

Some of the properties of PAM and its varying formulation discussed above makes it ideal for a wide range of industrial application, for example, for the treatment of potable water, dewatering of sewage sludge, washing and lye-peeling of fruits and vegetables, clarification of sugar juice and liquor, as a thickening and suspending agent in animal feeds, manufacturing of paper, mining and drilling applications.

A type of water insoluble, cross-linked polyacrylamide (CL-PAM) formulation is capable of producing a polymer network with cross-linkages similar to a sponge which has a great affinity for water. These types of PAM compounds can absorb water many times more than the polymer's weight and thus, they are useful in manufacturing of children's nappies and landscaping products, e.g. potting mixes. Using this type of PAM, a recent glasshouse studies by Sivapalan (2006) showed a substantial increase in water storage and reduction of percolation losses for a sandy soil. Application of cross-linked PAM effectively increased the interval between successive irrigations, yield and water use efficiency of soybean crop. International research with this type of PAM suggests that the water absorbed by cross-linked PAM is released when a salt is added to it and researchers appear to be critical of some of the exaggerated claims of water conservation made with this type of PAM within the commercial product sectors (Wu 2001).

1.3 AGRICULTURAL USE OF PAM

The agricultural use of PAM to improve land and water management is similar in many ways to other synthetic and natural products commonly referred to as soil conditioners. Although soil conditioners are thought to affect physical properties, some soil conditioners can affect physical and chemical properties of soil simultaneously (e.g. gypsum and lime). However, one of the key features in the use of PAM contrasts with many other soil conditioners is that a small quantity of PAM (in kg ha^{-1}) is often required to obtain the desired effects whereas other types of conditioners may need to be applied in large quantities (t ha^{-1}), similar to fertilizers (Sojka et al. 2007). The experience gained from various agricultural and environmental research with PAM in USA is summarized in Table 1 (USEPA 2003).

Table 1. Potential benefits and manageable adverse impacts of using PAM for land and water management.

PAM's functions	Beneficial effects[a]	Manageable adverse impacts
Reduces sediment concentration in runoff and overland flow (irrigation)	Decreases turbidity / improve clarity of runoff water Decreases transport of N, P, salts, pesticides, weed seeds and pathogens Decreases Biological Oxygen Demand (BOD) and eutrophication	No adverse impacts
Improves soil structure	Increases infiltration Decreases runoff	Increases drainage and leaching Over application can reduce infiltration in coarse textured soils
Improves binding of fine soil particles	Decreases soil erosion by water and wind Decreases turbidity of water bodies (e.g. lakes and water storages)	No adverse impacts
Increases soil water storage	Improves irrigation efficiency Decreases plant stress Improves plant growth	No adverse impacts

[a]Reduction of evaporation and seepage from farm dams are other possible benefits that require further research.

In irrigated agriculture, small quantity of food grade quality anionic PAM is often used by introducing it in irrigation water at the inflow end of furrow irrigated field to reduce erosion of channels (Peterson et al. 2003; Leib et al., 2005). Lentz and Sojka (1994) used 1-2 kg ha^{-1} per irrigation event to reduce erosion from irrigated furrows by 94%. Multiple application of PAM with sprinkler irrigation at concentrations of 3-3.5 ppm has been also found to reduce runoff and erosion by more than 50% (Bjorneberg et al. 2003). In some applications, reduction in erosion is clearly due to flocculation that increases settling of sediment within the ponded part of the field/channel. In other applications, reduced sediment generation with PAM has been attributed to reduction in runoff due to an increase in infiltration (Santos et al., 2003). Recent research by Sepaskhah and Bazrafshan-Jahromi (2006) with PAM under simulated rainfall shows that greater quantity of PAM may be required on steeper slopes to enhance infiltration as PAM has a better capability in reducing erosion than runoff.

Introduction of PAM with irrigation water usually requires much smaller amount of PAM than that would be required to treat the whole field to the depth of tillage. As the anionic PAM and the soils have similar (negative) charges, the presence of calcium ions (Ca^{++}) in soil as a bridging cation or PAM supplemented with dissolved calcium improves the overall performance of PAM in erosion control as it greatly enhances flocculation of soil and sediment (Sojka et al. 2007). In dispersive soils (e.g. sodic soils), PAM combined with gypsum has been found to be highly effective in reducing turbidity (Sivapalan 2005).

Medium and fine textured soils (loam to clay) with low organic matter and relatively high cation exchange capacity are prone to dispersion under the impact of rain and irrigation. Aggregate break down in soil caused by rain or irrigation, releases fine soil material of clay and silt size which would often redistribute and enter the space between existing soil aggregates causing sealing of surface soil and crusting. Infiltration of rain or irrigation water is often slow and highly variable causing uneven wetting of raised beds and water logging of low lying areas in the field. Application of PAM in irrigation water has shown to stabilize soil structure reducing sealing of surface soil and improving infiltration and redistribution of water (Bjorneberg et al. 2003).

There are also additional benefits of using PAM in irrigation water as not only it reduces channel erosion, but also reduces the off-site impacts by reducing export of carbon, nutrients and pesticides (Oliver and Kookana, 2006a, 2006b). Chemicals which are strongly adsorbed to soil (e.g. endosulfan) remain in soil, whereas chemicals which are weakly adsorbed and soluble tend to move with water with the potential to contaminate ground water.

1.4 ENVIRONMENTAL AND HEALTH IMPLICATIONS

Anionic PAM presents little health risk to the environment and not very toxic at the concentrations commonly used. Anionic PAM remains largely attached to soil or sediment and therefore, scope for PAM to enter waterways remain small. Nonionic and cationic PAMs tend to pose greater risk to aquatic organisms than anionic PAM (Sojka et al. 2007). However, the degradation of PAM in soil is believed to be slow and there are very few experiments conducted examining the degradation of PAM residue in soil. Much of the research focus with PAM degradation is on acrylamide (AMD) as it is known to be toxic. An isolated case of PAM degradation into AMD is thought to have been due to its combination with the herbicide glyphosate affecting solubility of PAM.

2.0 KNOWLEDGE AND EXPERIENCE WITH THE USE OF PAM IN THE AUSTRALIAN COTTON INDUSTRY

Researchers, manufacturers, suppliers and growers have been using and experimenting with PAM on Australian cotton farms since 1995 (Kelly 1996) to mitigate irrigation induced soil erosion and transport of pollutants from cotton fields (e.g. fertiliser, pesticides and *Fusarium*), stabilise soil structure, improve water infiltration into soils with poor surface structure and reduce seepage and evaporation from storages and channels. The dosage of PAM seems to be one of the most important factors capable of providing such a wide range of contrasting benefits.

The usage of PAM has peaked at approximately one in every five fields planted to cotton in one season (Andrew Tout Personal Communication). In fact, PAM is being used by some growers in almost every cotton growing region in Australia (Table 2). The majority of growers who are using PAM on their irrigated cotton fields are doing so to either to increase infiltration in soils that have surface soil structure issues (hard setting/sodic/medium to fine textured soils that may seal) or to reduce irrigation induced soil erosion. The latter has become more relevant where growers have been using PAM to reduce soil movement in furrow-irrigated fields where higher flow rates from larger or multiple siphons over much shorter irrigation durations are being used to improve water use efficiency.

Table 2. The extent to which PAM is used in the Australian Cotton Industry.

Region	Source	Perception of Use
Northern	**Stephen Yeates, Research Liaison Coordination Officer, CSIRO**	In the Burdekin, cotton is currently not grown commercially. There are a few isolated test farms and therefore PAM has not been used here in Cotton farming systems yet. PAM is used in other crops in these regions and its use will need to be evaluated in commercial cotton when this eventuates.
Emerald	**Doug Sands/ Susan Mass, Development Extension Officers, QDPI&F and Andrew Tout (Graincorp and former PAM distributor)**	A lot of people especially on the western side of the irrigation scheme with the steeper country are using PAM during watering up and for first in-crop irrigation to mitigate erosion and improve germination and do not use it after that because the beds seem to be stabilised once the crop is up. Other areas where the country is much flatter the use of PAM is not as prevalent. Those who are using PAM here will use it at watering up to decrease soil loss either due to soil limitations or because they have gone to bigger or double siphons to improve water use efficiency.
Darling Downs	**Graham Harris, Senior Extension Officer, QDPI&F Andrew Tout**	Limited use in cotton fields and the only known PAM reseller is trialling it in storages for the minimisation of seepage losses.
McIntyre Valley	**Emma Brotherton, Development Extension Officer, RWUEI QDPI&F and Andrew Tout**	The use is widespread in the number of growers who have tried and used. The results have been varied and some growers have not been able to make PAM work. Increasing infiltration has been the main aim. Other issues have been with application equipment, dosage rates, water quality, quality of product and storage of product.
St George Dirranbandi	**Scott Haynes, Grower Services Manager Queensland Cotton and Andrew Tout**	The use of PAM is quite common where infiltration is an issue, particularly on red soils. The economic returns from PAM application has been difficult to justify due to mixed results and problems with practical application (dosage and equipment).
Gwydir	**Julie O'halloran, Industry Development Officer NSW Ag and Andrew Tout**	PAM use is substantial. Growers are trying to mitigate erosion following cultivation and/or because they are using high flow rates to improve water use efficiency. Some growers are using it to increase germination at watering up. Decreasing the spread of *Fusarium* has also been another reason for use.
Namoi	**Tracey Farrell, District Agronomist NSW Ag and Andrew Tout**	In the upper Namoi, only a small proportion of growers are using it on sodic soils. Around Narrabri, most people have tried it and some have stopped using it due to poor economics or due to the fact that when the product changed from powder to liquid, they were not able to get the same results.
Macquarie /Bourke	**Andrew Tout**	At Bourke, the main aim was to decrease infiltration on well-drained soils but was not used successfully due to incorrect dosage resulting in increased infiltration. Powder was used successfully to reduce seepage from channels. PAM has also been used successfully to increase infiltration on red soils. There have been less than optimum results on some paddocks and this has caused some frustration.
Southern NSW	**Michael Grabham, Irrigation Officer, NSW Ag and Andrew Tout**	Some use in the Lachlan, Murrumbidgee and Hillston on hard setting soils to improve infiltration. It has been also used to mitigate erosion on steep country.

The use of PAM to reduce seepage from dams and channels has been investigated internationally since the 1970's. Various sectors of the Australian Cotton industry have been making similar investigations for several years. The results from these limited trials and demonstrations are also similar to the experience overseas in that they are promising but largely inconclusive in terms of best practice at the implementation stage. A greater effort is being championed by PAM suppliers in partnership with industry to further investigate this potential (Skip Webb CW Pacific Pty Ltd Personal Communication). Because PAM treated water increases in viscosity, it may be assumed that this water would not evaporate as readily as untreated water. Tests on PAM's effectiveness in mitigating evaporation have been purely in a controlled research context in small (10 m^2) evaporation tanks and have not occurred on farm dams or channels at this stage.

This section presents an overview of the outcomes from various PAM trials and demonstrations that have taken place throughout the cotton industry. Although attempts have been made to capture as many observations and trials as possible, due to time limitations the list cannot be considered as complete. The results have been grouped according to the expected benefit of using PAM and listed by region and soil type. The rigour of testing employed in each investigation of PAM is also indicated.

2.1 REDUCTION OF EROSION AND POLLUTANT TRANSPORT

In 2001, a major on-farm research project funded by the Cotton Research and Development Corporation aimed to test the effectiveness of several soil erosion mitigation techniques including the use of PAM, was completed (Waters 2001). In this work at Emerald, it was demonstrated that the sediment load and sediment concentration in tail water from the furrow irrigated cotton fields was reduced by 80% when 0.5–1 kg PAM per hectare was applied with irrigation water. Earlier Hugo (1999) achieved similar results in field scale trials at Warren and Kingsthorpe (Darling Downs), although, at Warren, a similar outcome depended on the application rate of PAM exceeding 3 ppm (3 kg/ha).

An added benefit of reduced sediment load and sediment concentration in irrigated crops is the potential reduction in pollutants that would otherwise leave cotton farming systems via runoff and drainage. Waters (2001) found that reduction in off-site transport of some of the pesticides from cotton field was directly proportional to reduction in sediment load and sediment concentration. This is expected as some pesticides and also some of the organic forms of nutrients are usually attached (sorbed) to soil and sediment particles. This study also showed that pesticide concentrations, although highly variable, were often highest early during the cropping season and just after the application of chemicals. This study also evaluated various traditional practices to reduce erosion and pollutant transport from cotton fields (including stubble retention) and recommended the need for an integrated approach to erosion and pollutant transport that combines well known methods of erosion control with PAM application.

It should be noted that although these results establish that PAM can significantly reduce irrigation-induced sediment movement from furrow irrigated cotton farming systems in Australia, it also demonstrated that rainfall induced erosion was not influenced significantly by the use of PAM as seasonal sediment load and pesticide concentration increased when rainfall to irrigation runoff ratio was high (Waters 2001). Rainfall simulator studies of Hugo (1999) support these findings.

Farmer demonstrations and trials conducted in collaboration with Agribusiness and/or extension programs throughout the cotton industry have anecdotally supported these more rigorous investigations (Table 3). Andrew Parkes, farm manager at Keytah, Moree (Personal Communication) observed that all irrigation induced erosion ceased after the use of anionic PAM. A cost benefit analysis of this reduction in sediment at Keytah was shown to result in a net profit of $75.57/ha due to a reduction in fertiliser/pesticide losses and a reduction in dredging costs (Skip Webb Personal Communication).

Sarah Hood, Department of Primary Industries Rural Water Use Efficiency Extension Officer at St George and Dirranbandi from 1999 to 2003 found that sediment concentrations were reduced by three quarters when 1 kg/ha of PAM was applied with irrigation water to sodic grey clays (Hood 2003). In one of the more rigorous farmer driven demonstrations that was reviewed Skip Webb (Personal Communication) measured a 90% reduction in soil movement from red soils when PAM was applied at 3.2 ppm and a 65 to 95% reduction in soil movement from grey soils in the Border Rivers region when PAM was applied at 1.8 ppm.

Although PAM has been unsuccessful in mitigating rainfall induced erosion, it has been clearly demonstrated that irrigation induced erosion can be significantly reduced by PAM on a range of soil types throughout the cotton industry. It appears that this result may be sensitive to the application rate of PAM (dosage) as erosion mitigation may require a minimum concentration of PAM in the irrigation water. A strong correlation appears to exist between reduction in sediment load in the irrigation tail water and the reduction in loss of certain contaminants which are mobilised with irrigation water and sediment (this includes some pesticides and fertilisers). This information has been used to determine projected loss of productivity (Waters 2001) and has led to commercial advertisement of the cost benefit analyses in using PAM to reduce sediment load and loss of nutrients and pesticides from cotton fields.

2.2 CHANGING SOIL INFILTRATION CHARACTERISTICS

It has been observed that when PAM is successful in reducing erosion, it also accompanies an increase in infiltration, particularly in increasing soil water retention and storage in sandy soils (Table 4). Dowling (1996) reported that when erosion could be successfully reduced by PAM, the infiltration increased to such an extent that siphons needed to be doubled up in order for the irrigation water to advance within the field to the same extent as the untreated water. It would be most advantageous to have an increase in infiltration in soils that are hard setting and/or sodic and also an increase in soil water retention in sandy soils. However, PAM’s use in the Australian cotton industry is not confined to these soil types and therefore, it is not known whether application of PAM in these soils will lead to an increase in drainage beyond the root zone. As Waters (2001) stated, “The impact of PAM on deep drainage needs further investigation.”

It should be noted that there are some observations that suggest increases in deep drainage may not be as issue (Dodd 2007, Janelle Hare Personal Communication, and Joe Robinson Personal Communication). However it is highly likely that a reduction in infiltration is a result of timing of application and/or incorrect dosage of PAM. Dowling (1996) reported a reduction in infiltration when using high dosage of PAM on the Darling Downs and Sojka et al. (2007) cited a number of research work that concluded that if soil structure is already damaged then PAM would have little to no effect on infiltration and on some occasions, it may even reduce infiltration. Such inconsistent results are a source of confusion in commercial application of PAM without even considering the impacts of variable water quality. It has been demonstrated (Shane Phillips Personal Communication) that irrigation with poor water quality may cause an increase in infiltration. As most people interviewed have not tested their water for its quality this may be an important issue in deriving full benefits of PAM use. This remains a challenge in the commercial use of PAM. Impact of PAM on infiltration is highly sensitive to dosage, water quality and soil type, but not as sensitive for erosion control.

There are various documents on anecdotal and crudely measured observations of the impact of PAM on infiltration and wetting of hard setting soils or soils with poor surface structure across the industry. Kelly (1996) with Pat Hulme, at a demonstration site in the Macquarie Valley, found that infiltration can be increased by between 14 to 43 mm when PAM is applied with irrigation water on hard setting soils depending upon which irrigation it is applied with. Hood (2003) found that on hard setting red soils at St George infiltration can be increased by 20mm. It should be noted that at this site a green manure crop and better tillage practices were also being used in conjunction with PAM. Pat Hulme (Personal Communication) has also found that Hillston soils with infiltration issues have been able to be stabilised with small amount of PAM dissolved in the water before it enters the drip system.

There is also some evidence of increase in infiltration on soils that do not suffer from low infiltration characteristics. For example, the rate at which irrigation water advances is directly related to the rate of infiltration. Okello-Okanya (2002) and Hood (2003) measured significant differences in the rate at which water advanced between PAM treated and untreated sections of the same field and therefore inferred that infiltration was higher when PAM was used. Although, neither of these investigations assessed the soil type and flow rates between the treated and untreated sections, it is not possible to attribute increase in infiltration to the use of PAM and conclude accordingly.

Furthermore, there have been several observations where the use of PAM has resulted in a reduction in infiltration. Dowling (1996) demonstrated that excessive dosage of PAM resulted in surface sealing in the paddock. Andrew Tout (personal communication) also reported several examples, where growers have either due to a lack of knowledge of the amount of water they are applying during an irrigation event or by following the adage “more is better” may have possibly sealed the ditches and/or reduced in-field infiltration during the irrigation event.

Recently the field scale application and performance of PAM in relation to infiltration has been investigated by Janelle Hare, Department of Primary Industries and Fisheries Development Extension Officer and member of the Cotton CRC Water team on the Darling Downs. These results have yet to be finalised.

It is imperative that the impacts of PAM on infiltration on a commercial scale are better understood by the industry and in particular, how these impacts can be compromised by the use of incorrect dosage and limited knowledge of water quality and/or soil type. There are two reasons why this is important. Sealing and sodicity are common soil characteristics that compromise the productivity of irrigated cotton and the rigorous assessment of mitigation of these soil conditions by PAM represents an opportunity that needs quantification. Secondly, it needs to be investigated whether increased infiltration on soils without sealing and sodicity issues are increasing drainage through cotton soils. It also needs to be investigated that whether decrease in infiltration at high enough dosage is a cost effective strategy to mitigate deep drainage on leaky soils. However, it should be remembered that all of these issues can be addressed with alternative strategies such as green manuring or gypsum. Ultimately, the best practice may be a combination of some or all of these strategies.

Table 3. Results of the recorded observations, demonstrations or trials assessing the effect of PAM on sediment and or pollutant transport in tailwater from Australian cotton fields.

Source	Organisation	Region	Soil Type	Dosage	Results	Comments
Waters 2001	Department of Natural Resources and Water	Emerald	Heavy grey clay	0.5 – 1 kg/ha	80% Reduction in Sediment Load. Sediment concentrations were reduced from 2.6 g/L to 0.5 g/L. Endosulfan concentration was reduced by 60%.	CRDC funded project with a high degree of rigour. It was suggested that PAM be considered as one tool in the erosion/pollutant control tool box. PAM applied in irrigation water did not significantly mitigate rainfall induced erosion.
Okello-Okanya 2002	Department of Primary Industries and Fisheries	Emerald	Open Downs – Grey Clay	Unknown	30% increase in average advance to end of paddock. It was inferred that infiltration was higher and therefore less erosion. It has been suggested that the reduction in erosion does occur on more permeable soils because of an increase in infiltration.	Non-replicated. It was not clear wether flow rates had been checked to see if this may be impacting upon advance. Water Quality and soil types were not fully explored. No erosion/pollutants measurements taken.
CW Pacific Pty Ltd 2003 Add Campaign	Keytah Farming Company	Moree	Black Clay	1.8 ppm	Virtually stops all water induced erosion.	No measurements taken.
CW Pacific Pty Ltd Personal Communication	CW Pacific	Border Rivers	Red Hard Setting	3.2 ppm	90% reduction in sediment concentration.	Non- replicated but well managed field scale trials.
CW Pacific Pty Ltd Personal Communication	Cw Pacific	Border Rivers	Grey	1.8 ppm	65 – 95% reduction in sediment concentration.	Non- replicated but well managed field scale trials.
Hugo 1999	University of Sydney	Warren	50.2% Clay	1g/L or 3g/L	Statistically significant reduction in soil erosion by 85% at 3g/L and pesticide movement.	Rigorous. PHD study with the dosages closely measured.
Hugo 1999	University of Sydney	Kingsthorpe	Self mulching clay	3 g/L	Significant reduction in soil erosion.	Rigorous – pesticide movement mitigation needed further investigation due to the postulation that pesticide is moved early in the tail water generation.
Dowling 1996	Australian Cottongrower	Darling Downs	Clay	5,10 and 40 ppm	Reduction in erosion occurred at low flow rates but increased dosages worked so well that the soil sealed over as well.	Infiltration increased so much on heavy clay soil that the siphons had to be doubled up to get the water through at the same time as the untreated section. Dosages for results were identified to be between 1–3 ppm (kg/ha). Application was problematic.

Table 4. Results of the recorded observations, demonstrations or trials assessing the effects of PAM on infiltration in Australian cotton fields.

Source	Organisation	Region	Soil Type	Dosage	Results	Comments
Kelly 1996	New South Wales Department of Agriculture	Macquarie	Red Hard Setting Soil	1 ppm (1kg/ha)	Increase in infiltration by 43mm on first irrigation and 16mm in second irrigation.	Statistical analysis not undertaken – not replicated.
Anderson and Ginns in Kelly 2003	Department of Primary Industries and Fisheries	Emerald	Sandy Loam Soil	1 litre/ML (1 ppm)	Increased infiltration or reduced runoff by 25% on a sandy loam soil under a centre pivot.	Statistical analysis not undertaken, not replicated. Although experimental method was clear.
Okello-Okanya 2002	Department of Primary Industries and Fisheries	Emerald	Grey Clay	Unknown	Yield difference of 2.7 bales/ha between treated and untreated parts of the paddock. 30% increase in average advance to the end of the paddock. 16% increase in water infiltration.	Not replicated. Was unclear how measurements had been taken.
Okello-Okanya 2002	Department of Primary Industries and Fisheries	Emerald	Grey Clay	Unknown	Germination better and crop evenness progressed more evenly throughout the season to maturity. Crop was early and yielded about 0.25 tons/acre more where the soil was treated.	Anecdotal.
Dodd 2007	University of New England	Glasshouse	Sodic cotton soils	0 to 0.25 %w/w "impractically high"	Improvement in the physical limitations of sodic soils with minimal impact upon nutrient availability.	Controlled glasshouse experiments.
Sivapalan	Charles Sturt Univerity	Trangie	Alfosol Degraded hard setting soil	7kg/ha	Significant improvement in soil physical properties. 84% increase in germination on soils where germination is a problem	Controlled glasshouse experiments.
Hood 2003	Department of Primary Industries and Fisheries	St George	Hard setting red dermosol	1kg/ha	20mm increase in infiltration.	Was used in conjunction with a green manure crop and better tillage practices so entire increase cannot be attributed to PAM alone.
Hood 2003	Department of Primary Industries and Fisheries	St George	Surface sealing grey sodic soils	1 kg/ha	One less irrigation per season. C-probe full point increased and 2 hours increase in advance to the end of the paddock.	Anecdotal. No measurements therefore it is not known how much if any of this slower advance resulted in higher infiltration.

2.3 EVAPORATION MITIGATION FROM DAMS AND CHANNELS

The Queensland Department of Natural Resources and Mines (Craig et al. 2005) commissioned the National Centre for Engineering in Agriculture (NCEA) to conduct an evaluation of the effectiveness of evaporation mitigation technologies for farm dams. Initially the NCEA sent out expressions of interests for any individual or businesses that had products or ideas (Brier 2004) in order to identify 5 technologies which were assessed by a technical panel to be most promising.

PAM was selected as one of the products to be assessed. The concept was that due to its chemical properties, PAM would increase the viscosity of water and therefore mitigate the ability of water molecules to escape from a water surface as evaporation. The level of viscosity required would dictate fairly high rates of application in the order of 100 ppm (Craig et al. 2005). This product was only tested in research evaporation tanks, 10 m^2 in area, at the University of Southern Queensland, agricultural engineering research site during this project.

This small scale trial demonstrated that PAM, when applied to a water surface at a rate of 100 ppm every seven days, could reduce evaporation on average by 37% (Table 5). There were very little adverse effects of PAM on the water quality parameters that were assessed in this study (Craig et al. 2005). Although the results were promising, the product was not tested on large farm dams and therefore it is not known what issues would arise in the practical application of PAM in large dams, including any possible impact on seepage. Currently this research is in the scoping stage.

2.4 SEEPAGE MITIGATION FROM DAMS AND CHANNELS

Seepage losses from farm dams and channels have been found to vary from less than 1 mm/day to in excess of 30 mm/day (Pat Hulme Personal Communication). Strategies to mitigate seepage from dams and channels in the Australian Cotton Industry have included compaction, partial abandonment and complete abandonment. Chemical strategies have also been investigated along with impervious lining to reduce seepage. PAM has been shown to be a cost effective seepage mitigation option in wider agricultural contexts (Sojka et al. 2007)

Controlled laboratory experiments using soil columns and PAM treated water showed that when concentrations of PAM increased the resulting infiltration on sandy soils decreased (Shane Phillips Personal Communication). Australian cotton growers have also been able to inadvertently achieve channel sealing when they have used high dosage of PAM. This has been one of the promising areas of PAM use in the wider agricultural context as there are number of trials which have demonstrated some degree of seepage control (Sojka et al. 2007). Although anecdotally growers and resellers within the cotton industry claim a reduction in seepage from dams and channels there has been only one on-farm reported investigation that was conducted on the Darling Downs (Table 6). This work lacked the scientific rigour to draw any definitive conclusions despite some promising results. Thus, further work is required to substantiate the apparent benefit and management of PAM in mitigating seepage losses from farm dams and channels.

Table 5. Results of the recorded observations, demonstrations or trials assessing the effect of PAM on evaporation from dams and/or channels on Australian cotton farms.

Source	Organisation	Region	Soil Type	Dosage	Results	Comments
Craig et al. 2005	National Centre for Engineering in Agriculture	Toowoomba	NA	100ppm every 7 days	37% reduction in evaporation. No significant impacts upon water quality (pH, temperature, dissolved oxygen).	Not investigated on farm dams – small plot trials. Need further investigation particularly for: • Environmental impacts • Frequency of application • How to apply it • Dirty water breakdown of product

Table 6. Results of the recorded observations, demonstrations or trials assessing the effect of PAM on seepage from dams and/or channels on Australian cotton farms.

Who	Organsiation	Location	Soil Type	Dosage	Results	Comments
Murray Boshammer (2005-2007) Personal Communication	Total Agricultural Supplies	Darling Downs	Silty Black Clay over a sand less	Various Rates	75% reduction in seepage.	Small ring trials next to dam – practical assessment yet to occur.
Murray Boshammer (2005-2007) Personal Communication	Total Agricultural Supplies	Darling Downs	Silty Black Clay over a sand lens	60kg/ha – where the EM problem was	Found that it was definitely better but was hard to quantify.	Rough measurements with $30 spirit level and a laser beam on a DTM and tape.
Alcorn 2005	Australian Cotton Grower	Darling Downs	Silty Black Clay	60 kg/ha	No effect on reducing seepage.	More definitive research is required in this area.

3.0 KNOWLEDGE GAPS AND RECOMMENDATIONS FOR USING PAM IN THE AUSTRALIAN COTTON INDUSTY

The knowledge about PAM, what it is and how it works and the possible range of its applications in agriculture are well understood. The usage of PAM in Australian Cotton fields is widespread and the extension of these applications for mitigation of evaporation and seepage from dams and channels are being investigated further. Given the current and expected future use of PAM by the cotton industry, it is of utmost importance that how PAM breaks down should be further investigated. The food grade product that is commonly used in agricultural applications is harmless as it contains little AMD, but there appears to be a dearth of information on the fate of PAM residue of smaller chain length and any environmental risks associated with these residues.

The use of PAM for evaporation and seepage mitigation is an economic alternative to existing methods of mitigation which needs thorough investigation. Some sectors of the industry have started or intend to progress research in this area. It would be considered strategic for the cotton industry to partner investigations in this area.

At the field level, although the benefits of PAM are well understood, the commercial application of PAM has produced varied results. Some examples of these are given below.

- Erosion is not reduced on some soils unless a particular dosage is achieved.
- Rapid or slow advance of water within the fields causes an increase or decrease in infiltration.

There is clearly a lack of field scale evaluations of the impact of PAM on infiltration. Although results of PAM usage have been discussed in various forums, any of the data collected and reported are not rigorous enough to draw firm conclusions.

The main reasons for such mixed results is because growers are not able to control application rate as they are unsure of the delivery rate of water to the field - this may have led to some growers using PAM at a higher rate under the premise that more is better. Even when application rate is maintained, PAM may interact with various salts and ions present in the soil and water producing variable results. Growers are encouraged to assess water quality and soil type to gain full benefit. Method and timing of application and performance of application devices are some of the important issues for application of PAM in crop fields and might be critical, particularly in relation to evaporation and seepage mitigation.

It would be of great strategic advantage to campaign for the increased measurement and monitoring of the effects of PAM by those using this product. This may be achieved through the development and distribution of a code of Best Practice for PAM use to growers throughout the industry to encourage the development of a data base which would allow information sharing in relation to PAM use. Growers also need to improve the way they monitor water delivery as it would allow accurate control over application rate of PAM.

Finally, PAM is used to obtain solutions to problems which can be achieved through other management options. Thus, other options should not be fully abandoned. For example soil surface structure can be improved through increasing organic matter and using gypsum. Thus, it makes sense to consider PAM as an additional option for undertaking integrated best management practice for irrigated soils, although the actual mix of strategies used will vary depending on specific situation which needs further investigation.

4.0 BEST MANAGEMENT OF PAM FOR THE AUSTRALIAN COTTON INDUSTRY

As established previously, best practice PAM use in the Australian cotton industry is yet to be developed fully. A coordinated effort in addressing the knowledge gaps identified in section 3 of this project would be considered timely in order to develop a consolidated code of practice for PAM use. However, in the absence of such a code, the following steps are recommended in the use of PAM.

Use of PAM on cotton fields to reduce erosion and/or manage infiltration characteristics should consider the following.

1. Establish what the PAM is to be used for. That is, modes of operation will dictate the dosage and management requirements.
2. Consider all options of control. There are several strategies that may achieve the same result that is being sought in the use of PAM. For example,
   - increasing siphon size and cutting the water off before it reaches the end of the field may decrease infiltration and thereby increase water use efficiency and reduce erosion on some soils;
   - wheat stubble can increase infiltration and reduce erosion on hard setting, red soils;
   - increasing organic matter through green manure cropping or gypsum applications may stabilise surface structure of some of the other soils.

   Therefore, a range of alternatives and/or a mix of approaches should be considered when designing remediation strategies.
3. Obtain a soil description, particularly the infiltration characteristics of the soil before and after PAM use.
4. Assess the water quality of the irrigation water.
5. Measure the rate at which water is being delivered to the field.
6. Design PAM dosage after the information in steps 1 to 5 has been amassed.
7. Collect enough data to assess the impact of use and therefore establish both economic and environmental benefit analysis of PAM. This is a logical step in considering the continued use of the product.

Use of PAM on cotton farm dams and channels to mitigate seepage or evaporation:

1. Understand that in relation to seepage and evaporation mitigation the theoretical basis and practical implementation is still being explored. In fact, PAM as an inhibitor of evaporation has not been investigated in farm dams and channels within the Australian cotton industry as yet. If PAM is going to be utilised to reduce evaporation or seepage from farm dams and channels then the grower will be required to design the method of application and an appropriate evaluation strategy. Therefore it is recommended that the grower seeks assistance from those with the appropriate capacity in this area.
2. Collect enough data to assess the impact of use and therefore establish both economic and environmental benefit analysis of PAM. This is a logical step in considering the continued use of the product.

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